

Ultrafast Short Pulse Laser Material Processing of Aerospace Materials

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Abstract

The aerospace industry has been at the forefront of laser material processing. At present it is an industry that is identified with the more traditional laser systems such as continuous wave (cw) Nd-YAG lasers for such applications as welding and cutting and pulsed Nd-YAG lasers for drilling and shock-peening. These laser systems have high average powers in the hundreds and thousands of Watts and high pulse energies in the tens of Joules. This has allowed them to process aerospace materials at commercially attractive cycle times, but the disadvantage of using these systems has been the collateral damage inflicted on a component due to micro cracking in turbine blades, delamination of thermal barrier coatings and their associated heat affected zones. One way to eliminate the problems associated with this type of damage is to process with ultra fast ultra short laser pulses where the laser material interaction time is of the same order as the electron-phonon coupling time. This paper investigates micro machining of a range of aerospace materials but paying special attention to lightweight composite aerospace materials. The paper compares the micromachining results from a new and novel picosecond high repetition rate fibre laser system and a femtosecond laser source.

Keywords: Ultrafast laser processing, Composite Material, Thermal Barrier Coatings, Recast, Delamination, Titanium Alloys. Micromachining Aerospace Components.

1 Introduction

Laser material processing in the aerospace industry has traditionally been performed by either lamp pumped or DPSS Nd-YAG laser systems. An application such as drilling of nickel-based alloys in aero engines is dominated by such laser. The typical pulse length for this type drilling is in the region of 0.5 – 1.0 ms with pulse energies typically in the 5 – 18J range for European manufactures. Laser cutting in the aerospace industry uses multi kilowatt Nd-YAG and CO₂ laser systems. The common factor with these two aerospace applications is that they can be termed macro-applications and are characterised by their high average power and hence high throughput.

Today the role of the laser in the aviation industry with respect to material processing is changing due to the potential introduction of new materials and changes in aircraft design such as Britain's autonomous unmanned aerial vehicle programme "Taranis". This paper investigates aerospace micromachining applications with a new pulsed fibre laser source with interesting characteristics for meeting the challenges of laser material processing in today's aerospace industry.

Fibre lasers, with their compact size, high efficiency, and maintenance-free operation, are ideally positioned to compete with traditional solid-state lasers in many application areas, including precision materials processing. The most obvious candidates to challenge solid-state dominance are fibre lasers based on

ytterbium Yb-doped fibre. Ytterbium-doped fibre lasers and amplifiers operate over a wide spectral range including the common wavelength of 1064 nm. The broad absorption band around 976 nm permits optical pumping of Yb-doped fibres with high-power, telecom-rated laser diodes, achieving optical conversion efficiencies close to the theoretical limit¹.

One of the most fortunate features of fibre amplifiers-both erbium Er-doped and Yb-doped-is a high gain combined with a low noise figure. This allows the use of "Master Oscillator Power Amplifier" (MOPA) configurations in which a low-power master source is followed by a high-gain, high-power fiber amplifier, allowing the parameters of both the master source and power amplifier to be independently tailored. The laser systems used in this investigation produced laser pulse of approximately 10ps with a selectable repetition rate in the region of 1MHz to 20MHz. The mean power of the system was 10W. This technology is under continuous development, pushing for even greater increases in mean power for the future.

The experimental work was performed on a femtosecond laser system so that we could make a direct comparison with materials processed by the Fianium high repetition rate pulsed fibre laser.

1.1 Basic Processes and Material Interaction

Femtosecond laser systems are limited in material removal rate by their low average power. The ablation

rate expressed as ablation depth per laser pulse at low and high fluences follows an approximate logarithmic dependence. It has been shown that the ablation of metals has two separate processing regimes [1,2]. At low fluences (typ. $\phi_0 < 1\text{J}/\text{cm}^2$) the penetration depth is proportional to the optical penetration depth, but at higher fluences (typ. $\phi_0 > 1\text{J}/\text{cm}^2$) the penetration depth is greater than the optical penetration depth due to the fact that it takes longer for the thermalised electrons to reach thermal equilibrium with the lattice and heat is also transferred by the ballistic transport of non-thermalised electrons. This leads to energy penetrating to a depth that is greater than the optical penetration depth and is known as the electron heat diffusion length or the effective heat penetration depth. A certain fraction of the heat is then lost by propagation to the surrounding material. This reduces the efficiency of the removal rate and leads to the reappearance of a heat affected zone.

Ultra short laser pulse-material interactions can be explain simply with the one dimensional two temperature model (Mannion, P et al [1]). In this model the electron and lattice are treated as two separate heat baths with temperature T_e and T_l . In order to use the model the thermalisation of the electrons must be fast compared to the pulse length and this is indeed the case for sub-picosecond laser heating of gold films. The two main equations are as follows:

$$C_e(T_e) \frac{\partial T_e}{\partial t} = -\frac{\partial}{\partial z} \left(k_e \frac{\partial T_e}{\partial z} \right) - g(T_e - T_l) + S(z, t) \quad (1)$$

$$C_l(T_l) \frac{\partial T_l}{\partial t} = g(T_e - T_l) \quad (2)$$

Where:

C_e : Electron Heat Capacity.

C_l : Lattice Heat Capacity.

k_e : Electron Thermal Conductivity.

$S(z, t)$: Absorbed Laser Energy Density per unit time.

The heat diffusion through the lattice is neglected in the second equation because heat diffusion occurs much more rapidly through the electron gas than through the lattice phonons due to the difference in between the heat capacities of the electrons and the lattice. Chichkov et al [2] showed that using the above model that there are two separate ablation regimes both governed by a logarithmic dependence. The first for low peak power laser fluences ($\phi_0 < 1\text{J}/\text{cm}^2$), the ablated depth per pulse L , is given by:

$$L \approx \alpha^{-1} \ln \left(\frac{\phi_0}{\phi_{th}^\alpha} \right) \quad (3)$$

Where:

α^{-1} : Optical Penetration Depth

ϕ_{th}^α : Ablation Threshold (low fluence regime)

At higher peak fluences ($\phi_0 > 1\text{J}/\text{cm}^2$) the second dependence is given by the expression:

$$L \approx l \ln \left(\frac{\phi_0}{\phi_{th}^l} \right) \quad (4)$$

Where:

l : Electron Heat Diffusion Length

ϕ_{th}^l : Ablation Threshold (high fluence regime)

In order to understand why the two regimes are present one must make use of the fact that the dynamics of the electron heating and cooling process are non-linear. At electronic temperatures much higher than the Fermi temperature, T_F :

$$T_F = \frac{E_F}{k_B} \quad (5)$$

Where:

E_F : Fermi Energy

k_B : Boltzman Constant

The electron heat capacity C_e is given by the following expression:

$$C_e = \frac{3}{2} N_e k_B \quad (6)$$

Where:

N_e : Electron Density

The electronic heat capacity is constant but the electron thermal conductivity, k_e grows with the electron temperature, T_e as:

$$k_e \approx T_e^{\frac{5}{2}} \quad (7)$$

While the electrons and the lattice are not at thermal equilibrium electronic heat conduction is taking place. The higher the temperature reached by the electrons (the higher the incident laser fluence) the greater the rate of electronic heat conduction according to equation (7) and (1). Also the higher the temperature reached by the electrons, the longer it takes for the electronic

subsystem to come to thermal equilibrium with the lattice, thus allowing more time for the electronic heat conduction to take place at its elevated rate. Thus whilst operating at higher fluences the ablation is characterised by the *electron heat diffusion length*, l .

At lower laser fluences the density of hot electrons is lower and the rate of electronic heat conduction is also lower. The electrons and lattice reach thermal equilibrium faster because of the smaller difference in electronic and lattice temperatures, thus allowing less time for electronic conduction at its reduced rate. Therefore the amount of energy transfer out of the optical skin depth and into the target is negligible and the ablation is characterised by the *optical penetration depth*, α^{-1} .

2 Experimental Set-up

2.1 Laser System

The Fianium ultrafast high beam quality laser consists of three main sub-systems: a passively mode-locked low power fibre laser (master source), a pulse-picker a high power cladding pumped fibre amplifier and a high-power free-space optical isolator. The beam quality delivered by the Fianium laser has an M^2 in the region of 1.2. with a wavelength of 1064 nm [3].

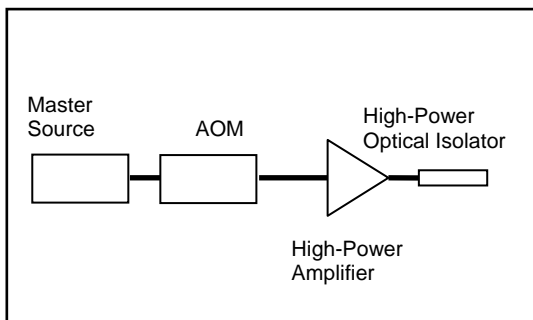


Fig 1: Basic design of the laser system.

The output channel is free-space delivered in a collimated beam through the output isolator mounted external to the optical head.

2.2 Master Source

The master source is a passively mode locked fibre laser based on a core-pumped Yb-doped fibre. The laser operates at a repetition rate of approximately 20MHz, providing pulse widths of 10 picoseconds with a pulse-to-pulse stability of the master source which is excellent.

2.3 Pulse Picker

The pulse-picker system, comprising control electronics, RF driver and Acousto-Optic Modulator (AOM) is positioned after the master source. The pulse picker provides the feature of dividing the fundamental repetition rate ($R_f=20\text{MHz}$) by an integer value, R from 1 to 40, resulting in pulse repetition rates of 20MHz, 10MHz, 6.7MHz.... down to 500KHz.

2.4 Power Amplifier

The high power fibre amplifier is based on a two-stage double-clad Yb-doped fibre, which is pumped by a high power multi-emitter laser diode pumping module. The pump module is air-cooled with inlet and outlet fans, mounted on the laser front and rear panels, forcing the air over the pump heat sink. The gain of the two amplifier stages is balanced and PC controlled to limit the output power from the amplifier as a function of pulse repetition rate.

2.5 Experimental Set-up

Figure 2 shows the experimental set-up used during the series of experimentation. The laser is a Fianium picosecond laser system which has an average power ranging from 0.08 to 8.3 Watts with a pulse width of 10 picoseconds. The pulse energy delivered by the laser system ranged from 0.1 μJ to 2.9 μJ . The 1.5 mm diameter output beam was expanded through a 2x Galilean telescope. The beam was then focused onto the samples through a 60mm focal length singlet. The samples were mounted on an Aerotech XYZ table.

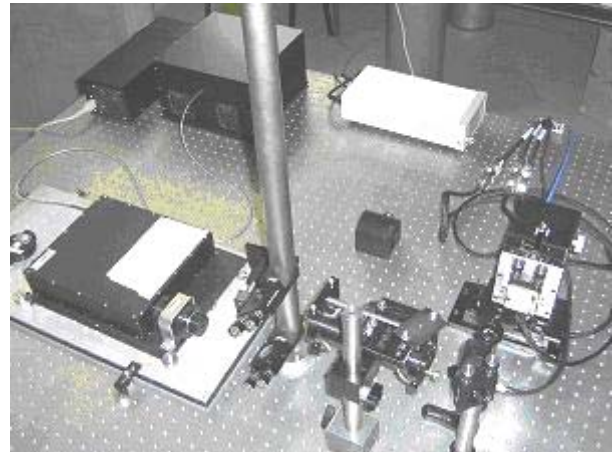


Fig 2: Picture showing the experimental set-up.

2.6 Aerospace materials

In these experiments we were interested in exploring the laser's capability in processing materials that are of interest to the aerospace industry. In this initial study we looked at titanium alloy Ti-6Al-4V, carbon fibre composite MTM44-1 and polymeric material AF 163. These last two materials are used in the construction of nacelle acoustic liners where the ability of drilling holes is an important enabling technology [4].

3 Experimental Results

3.1 Ablation Experiments of Ti-6Al-4V

Our interest in this laser system stemmed for the fact that it has an ultrafast capability and a comparatively high average power. A comparison of the material processing efficiency of the laser was performed with the laser is operating at two different frequencies of 500 kHz and 20 MHz. Two titanium samples are shown in

figure 3 and figure 4 with some processing parameters details and feature sizes given in table 1.

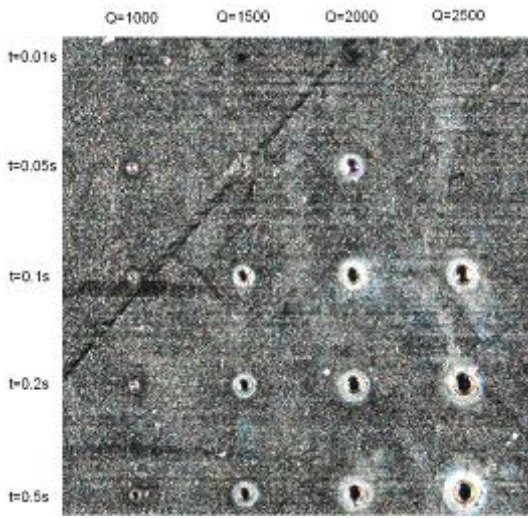


Fig 3: Titanium sample processed at 20MHz.

A comparison of the two plates shows that at the higher repetition rate and higher mean power the sample shows evidence of a melted rim section around the hole and a heat affected zone. Plate 1 (Fig 3) which was processed at 20 MHz for interaction times greater than 0.05 seconds and mean powers greater than 4.5 W shows both of these affects. The diameter of the craters seems to scale with the mean power of the laser system. A comparison of the crater diameters produced at a repetition rate of 500 KHz shows that the diameter of the crater entrance was on average 26 μ m for pulse energies of 2.9 μ J, (the maximum pulse energy output of the laser).

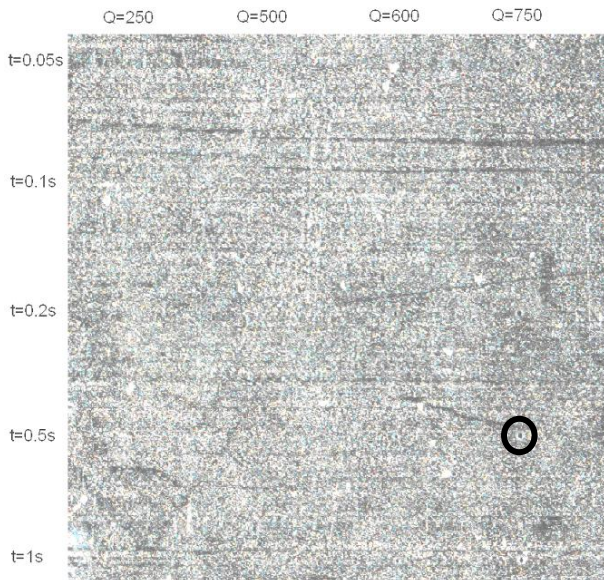


Fig 4: Titanium sample processed at 500KHz. Typical hole highlighted.

Craters drilled at the higher repetition rate of 20MHz and lower pulse energy of 0.125 μ J produced craters with average entrance diameters of 40 μ m. The depth of the craters shows that at the low pulse energies and high

rep rate the amount of material removed is small. At the shortest interaction time of 0.01 seconds only 1.5 μ m was removed. The diameter of the hole on the other hand was in the region of 35 μ m. This suggests that the material removed from the crater was mainly in the surface material due to conduction of heat in to the surrounding surface layer. This affect was due to the laser beam fluence being below the ablation threshold of the titanium sample.

At the lower repetition rate of 500 KHz (Fig. 4) and lower mean power of 1.45W the pulse energy was 2.9 μ J. This produced a deeper crater that was over 13 times deeper than the previously discussed crater. The diameter was in the region of 26 μ m which is in the region of the calculated spot size.

Tab. 1: Representative Process Parameters

Fig	Time (sec)	Q Value	Mean Power (W)	Energy (μ J)	Crater Dia (μ m)	Depth (μ m)
3	0.01	1000	2.5	0.125	35	1.5
3	0.05	1000	2.5	0.125	40	~
3	0.1	1000	2.5	0.125	40	~
3	0.2	1000	2.5	0.125	40	~
3	0.5	1000	2.5	0.125	43	10
4	0.05	750	1.45	2.9	25	15
4	0.1	750	1.45	2.9	26	21
4	0.2	750	1.45	2.9	26	20
4	0.5	750	1.45	2.9	27	21
4	1	750	1.45	2.9	27	20

This shows that unlike previously there was no energy transfer in a lateral direction to the laser beam and all of the energy was utilised in ablating the hole. This was due to the laser pulse energy being above the ablation threshold of titanium. Previous work [2] showed that the ablation threshold of titanium is 0.1021 J/cm² which fits in with our findings as the fluence of our laser beam at 2.9 μ J is 0.148 J/cm².

A further matrix of craters was produced at the lower repetition rate of 500KHz but with the interaction time increased to a region between 2 and 33 seconds. Over this range of interaction times the craters diameters remain constant producing an entrance of 26 μ m. This is the same as the calculated focused spot size for these experiments. The depth of the craters showed a very different behaviour. The depth of the craters initially increased producing a maximum depth at 4 seconds with a depth of 21 μ m. But as the interaction time was increased the crater depth decreased. This affect is possibly due to the accumulation of melt at the bottom of the crater which builds up forming a slug of titanium alloy at the bottom of the hole. To eject this material we need to increase the recoil pressure by either increasing

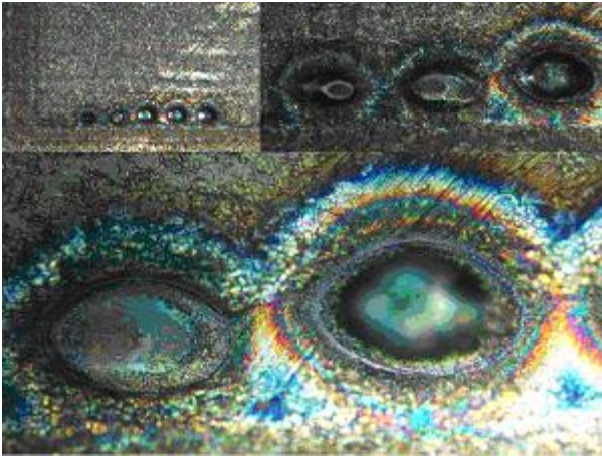


Fig 5. Lack of material removal – spot welds

the power density i.e. reducing the spot size, or by increasing the pulse energy. Fianium are developing fibre laser systems producing higher pulse energies that will help in this area of processing.

The ability to deliver energy in a precise and controlled manner on the micro-scale will allow for an interesting application picosecond micro-welding. Our experiments have shown that the energy is given up to the lattice, figure 5. Operating below the ablation threshold of the material will allow micro spot welding or continuous seam welding on thin foils or micro components. These applications would be of great interest to the electronics industry.

3.2 Ablation Experiments of Carbon Composites and Aerospace Polymers

Polymer ablation depends on two conditions, first the polymer must absorb the strongly at the laser wavelength, and secondly the energy within the pulse must exceed the ablation threshold of the material. We also studied MTM44-1, a toughened epoxy carbon

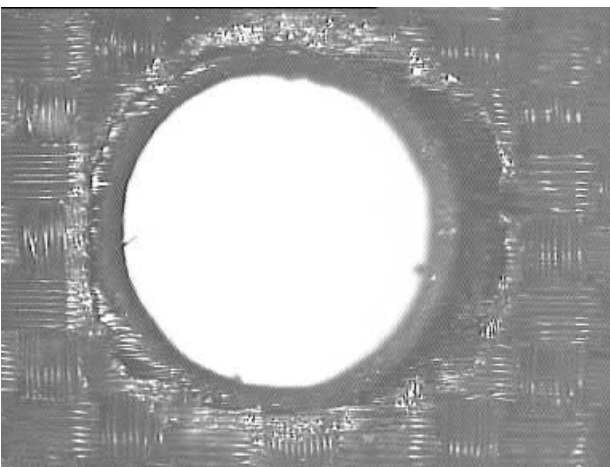


Fig 6: MTM44-1 x10mag trepanned with a millisecond pulse length.

composite system used in civil aircraft structures. The carbon composite material MTM44-1 absorbed well at 1064 nm. Material processing experiments preformed

with a Nd-YAG laser system operating at its fundamental wavelength but emitting pulse length in the millisecond range was observed to machine the carbon composite material. Figure 6 shows a hole that has been laser trepanned using this laser.

The edge of the hole shows signs of thermal damage. The hole shows signs of burn out on the circumference with fibres protruding into the hole. The hole also shows severe erosion around the rim of the hole.

Using the results produced by a Clark-MXR CPA 2010 femtosecond laser system as a baseline for short pulse laser processing we machined the carbon composite material MTM44-1 using the following parameters. The mean power of the laser was 100 mW, 100 μ J per pulse with a repetition rate of 1kHz with a pulse width of 150 fs. The wavelength of the system was 775 nm. A laser trepanning technique was used to produce all of the holes.

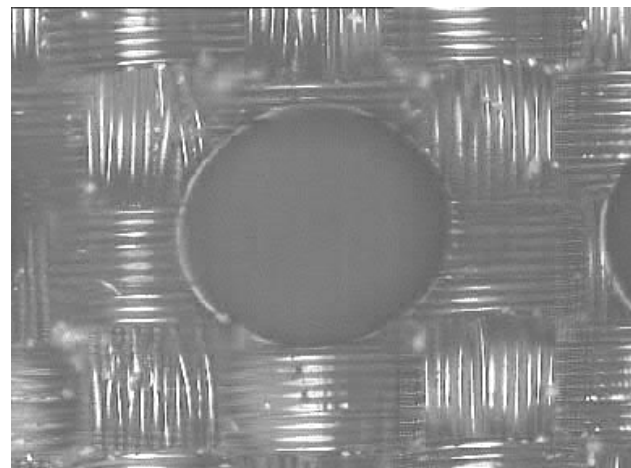


Fig 7: MTM44-1 x10mag Hole diameter 0.5mm

From the initial study of the holes produced by the above parameters the visual inspection of the hole quality in MTM44-1 appeared excellent, figure 7. The sample showed no sign of burning or taper.

The results from the picosecond laser system showed that with our present set up we are operating on the ablation threshold of this material. As a consequence the laser had a tendency to produce a large HAZ, figure 8. The figure clearly shows that the top surface of fibres have been melted exposing a bright reflective area. Work on this composite material will continue but using a different optical set-up that will produce a smaller focussed spot size and hence a higher power density at the focused spot. With this new set-up we hope to produce results similar to the femtosecond laser system, figure 7.

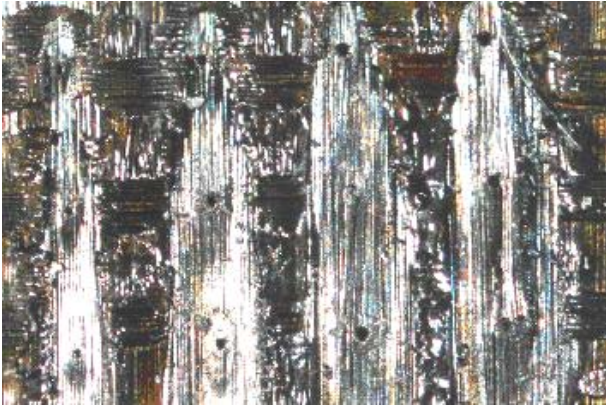


Fig 8: Carbon composite MTM44-1 showing signs of damage.

The polymeric material AF 163 has been found to have poor absorption at 1064 nm. Experiments performed on this material using a Nd-YAG laser system operating in the millisecond region found that most, if not all of the pulse energy was transmitted through a thin sheet of the material, without producing holes. The picosecond laser produced holes in the material also showed signs of thermal affects. In figure 9 a central ablated area can be seen but around this can be seen a ring where the optical properties of the AF 163 has been changed. This we believe has been caused by thermal conduction, The central hole also shows signs of charring around the rim.



Fig 9: Polymeric material AF 163 showing signs of thermal damage, surrounding the holes..

4 Conclusions

The Fianium ultrafast fibre laser, FEMTOPOWER 1060-8-PP is a new generation of material processing laser that has unique laser processing capabilities. Through the above experiments, we have concluded that: the Fianium fibre laser has a good beam quality; and is compact, robust and convenient to operate.

Even in its present configuration of operating near the limits of the materials ablation threshold it was still possible to achieve sufficient pulse energy for ablative machining of an aerospace alloy.

The results point to an interesting application in micro-welding. Below the ablation threshold, it was possible to process without material removal and this may represent a novel welding process.

Increasing the power density of the laser set-up will enable the laser to process polymers at the wavelength of 1064 nm at industrial relevant rates.

Due to its higher average power compared to traditional Femtosecond laser systems the Fianium picosecond fibre laser will have the ability of machining large areas in such aerospace applications as surface texturing for adhesives at industrial relevant rates.

5 References

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